

Space Nuclear Power Systems

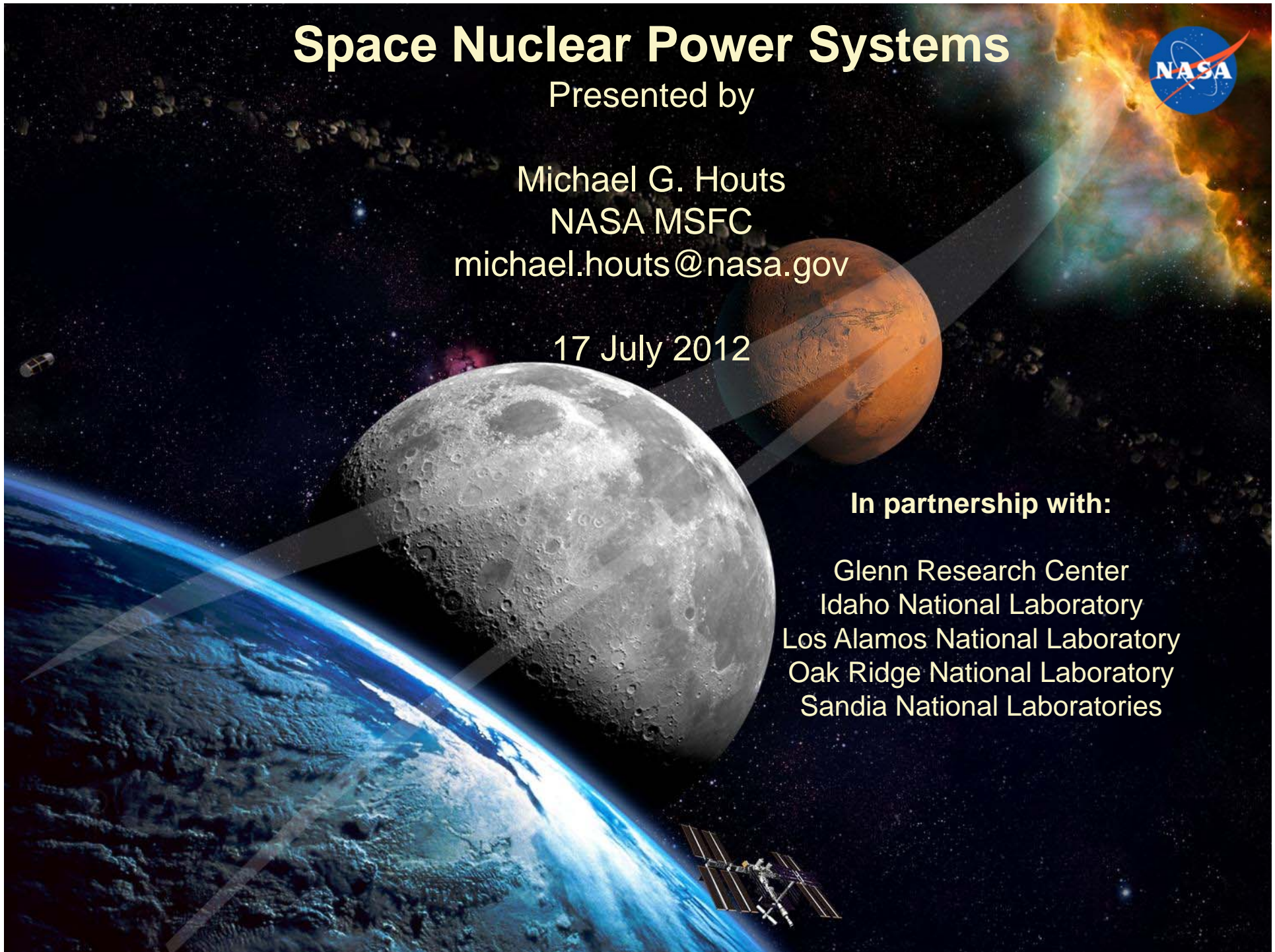
Presented by

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17 July 2012

In partnership with:

Glenn Research Center
Idaho National Laboratory
Los Alamos National Laboratory
Oak Ridge National Laboratory
Sandia National Laboratories



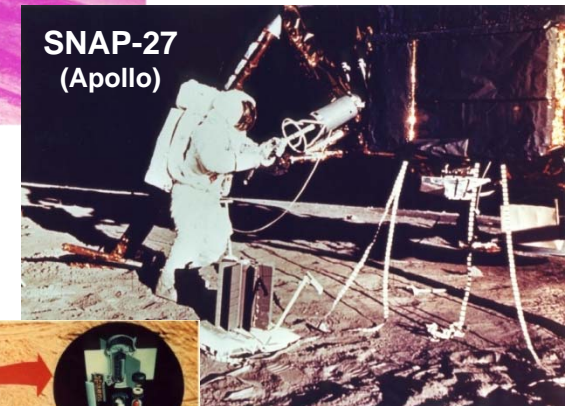
Space Nuclear Power

- **Radioisotope Power Systems**

- 44 Successful U.S. Radioisotope Thermoelectric Generators (RTG) Flown Since 1961
- Some Examples:
 - » Apollo SNAP-27 (1969-72)
 - » Viking SNAP-19 (1975)
 - » Voyager MHW-RTG (1977)
 - » Galileo GPHS-RTG (1989)
 - » Ulysses GPHS-RTG (1990)
 - » Cassini GPHS-RTG (1997)
 - » New Horizons GPHS-RTG (2005)

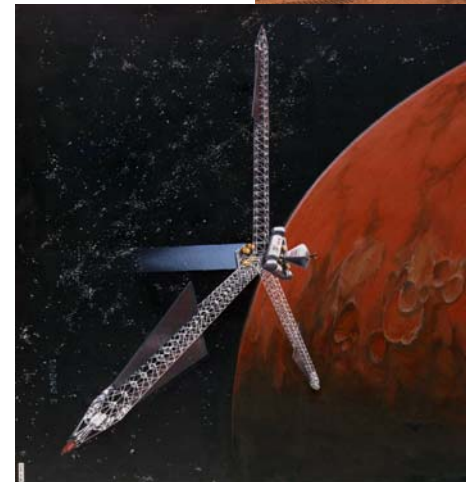
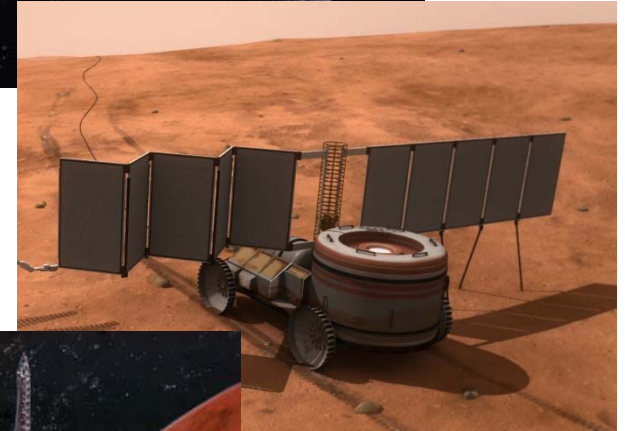
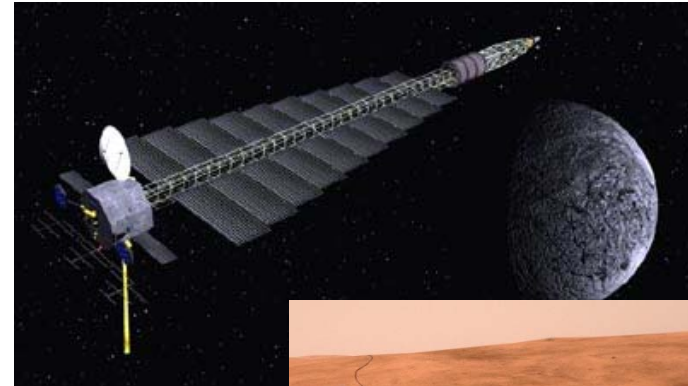
- **Fission Reactor Systems**

- SNAP-10A (launched 1965)
- Soviet Buk and Topaz (over 30 systems launched from 1967-1988)
- SP-100 (1984-1993)
- Jupiter Icy Moons Orbiter (2002-2005)
- Fission Power Systems (present)



Why Space Fission Power?

- **Abundant power to meet increasing mission demands:** scalable from kilowatts to megawatts and beyond
- **Potential for very high energy density and long life:** significant performance advantages compared to alternatives
- **Safe during all mission phases:** launched cold, remains subcritical until commanded startup, low residual radiation after shutdown
- **Operationally robust:** high reliability with capacity for contingency operations
- **Environmentally robust:** eliminates dependence on sunlight, resilient under adverse environments
- **Extremely flexible:** can be adapted to a wide range of mission applications using common technology building blocks
- **Affordable:** detailed studies show development costs are competitive with alternatives
- **Potential Terrestrial Spin-offs:** Low power, compact, autonomous reactors? Basic technologies?





Projected Applications for Fission Power Systems

1. Planetary/Space Science

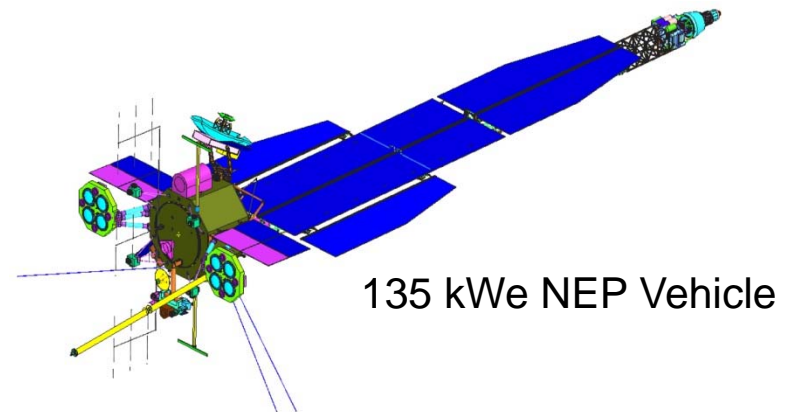
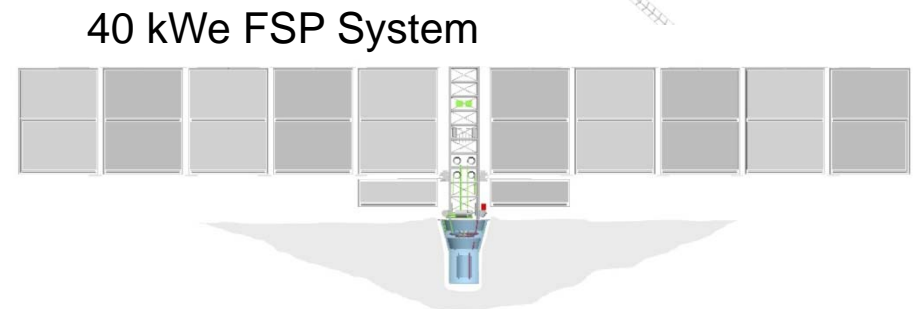
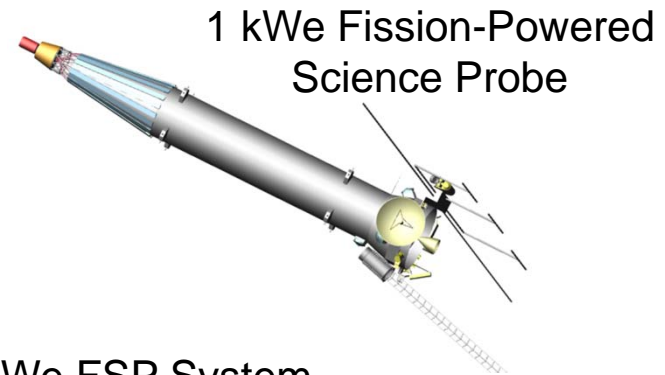
- <1 to 10 kWe
- 10 to 20 yr life
- Unmanned, Autonomous
- Above power range of interest for radioisotope systems
- Non-Obtrusive; will not interfere with Science Objectives

2. Fission Surface Power (FSP)

- 10 to 100 kWe
- 5 to 10 yr Life
- Human-rated
- Robust and Reliable; Mass is Secondary
- Adaptable to Multiple Missions and Environments

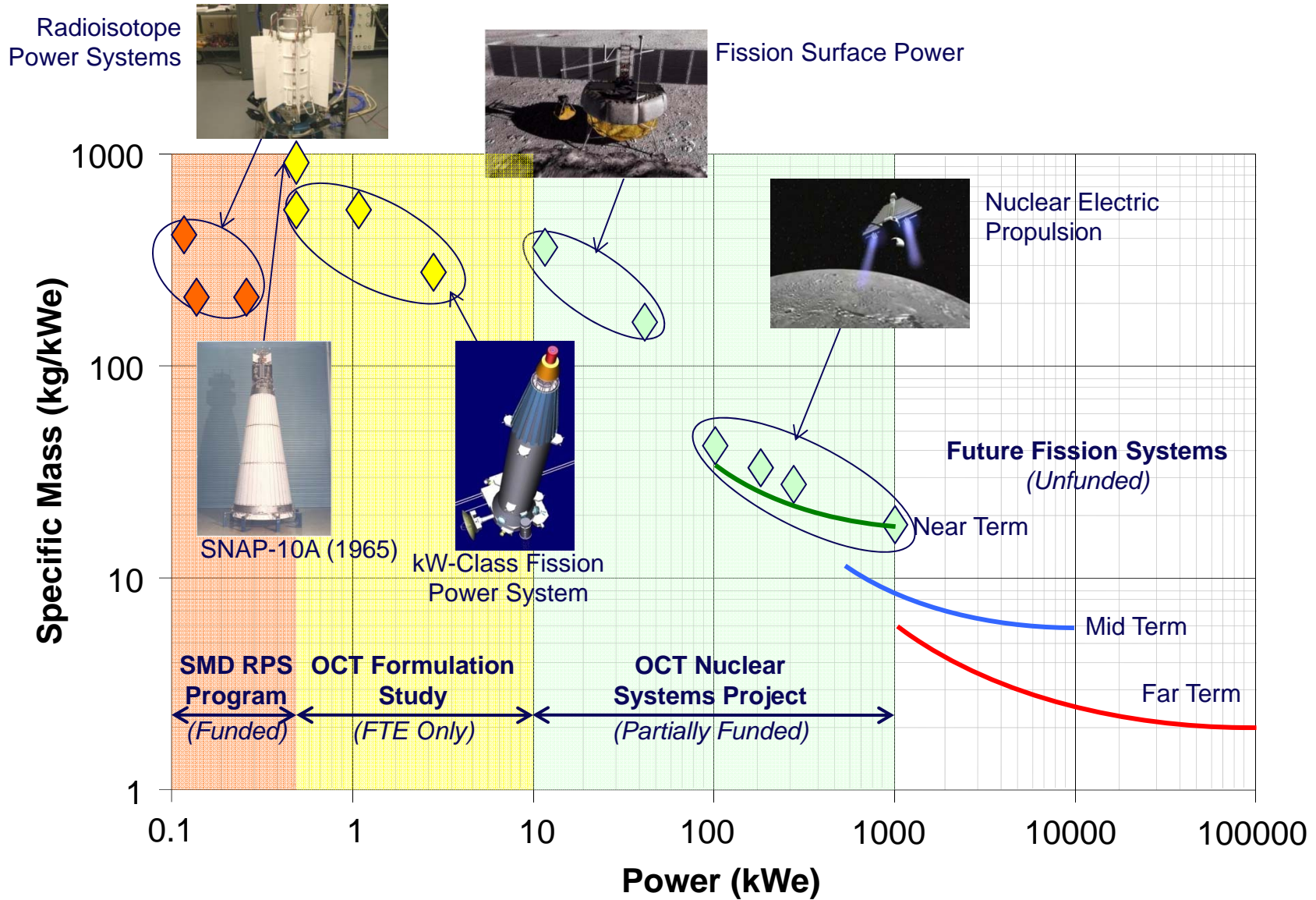
3. Nuclear Electric Propulsion (NEP)

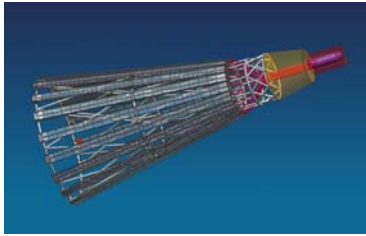
- 100 kWe to Several MWe's
- 5 to 15 yr Life
- Cargo or Piloted Missions to Mars
- Low Specific Mass (kg/kW); Must provide benefits over SEP
- Flexible Operations: Thrust, Coast, Science, Standby





Nuclear Power Performance Regimes

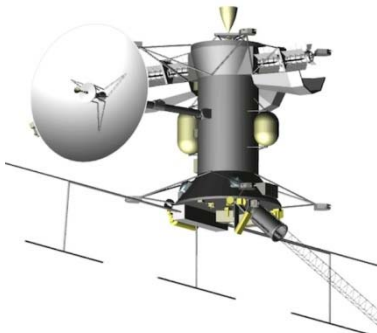




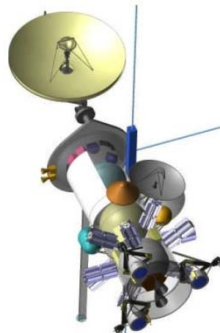
Small FPS Mission Pull



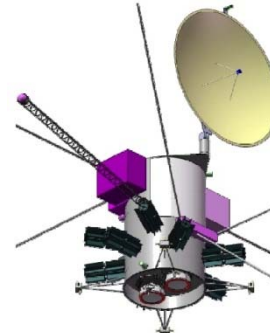
Science:



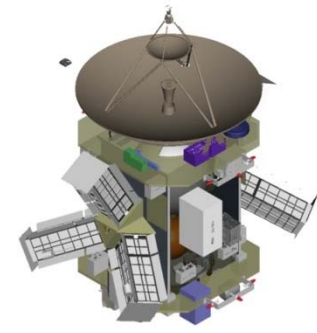
Jupiter Europa Orbiter
(5 to 6 RPS)



Neptune Systems Explorer
(9 RPS)



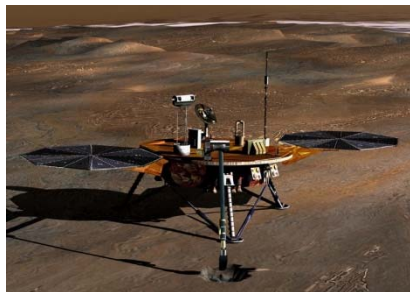
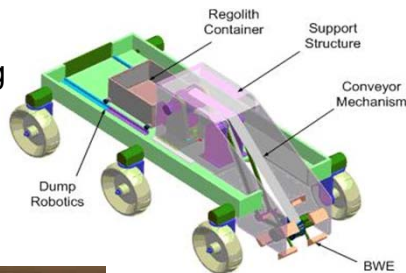
Kuiper Belt Object Orbiter
(9 RPS)



Trojan Tour
(6 RPS)

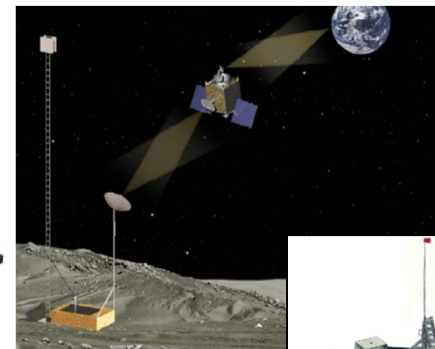
Exploration:

Remote Mining
Vehicles



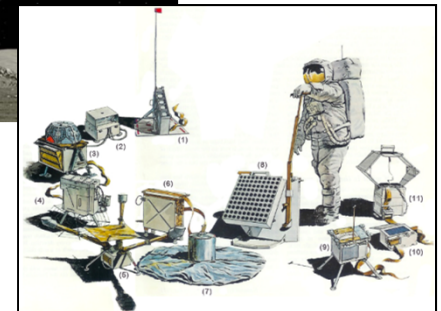
Site Survey
Landers

ISRU Demo
Plants



Comm Relay
Stations

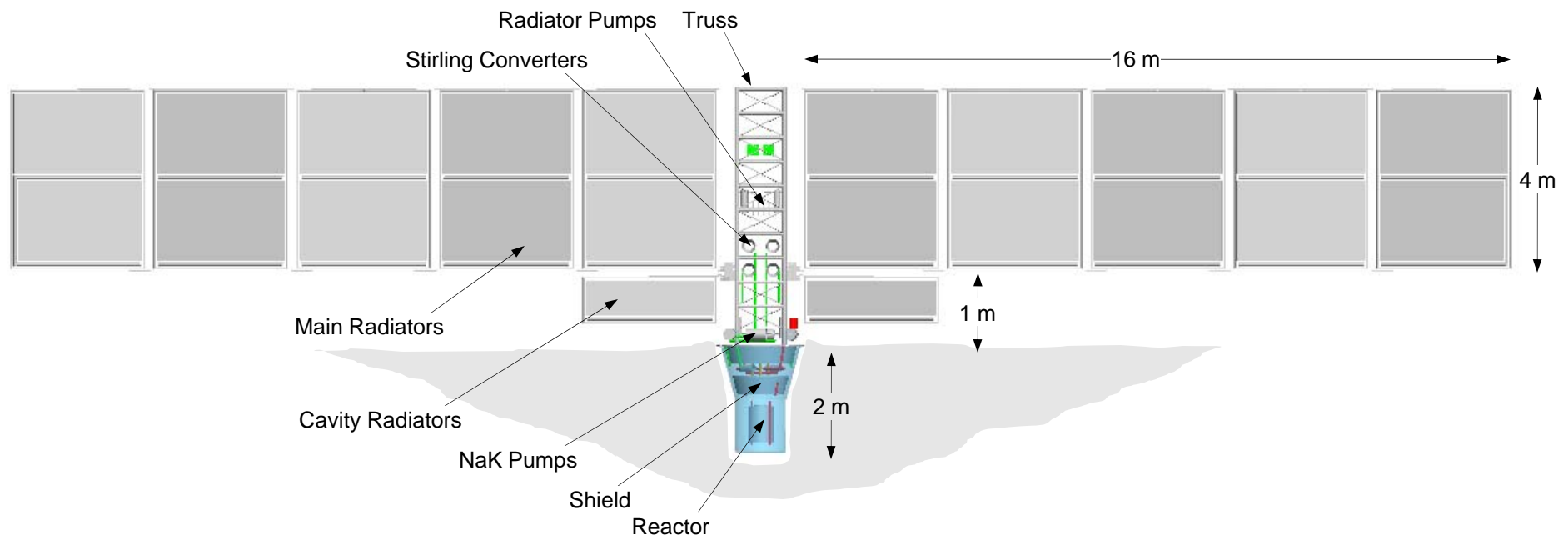
Remote Science
Packages





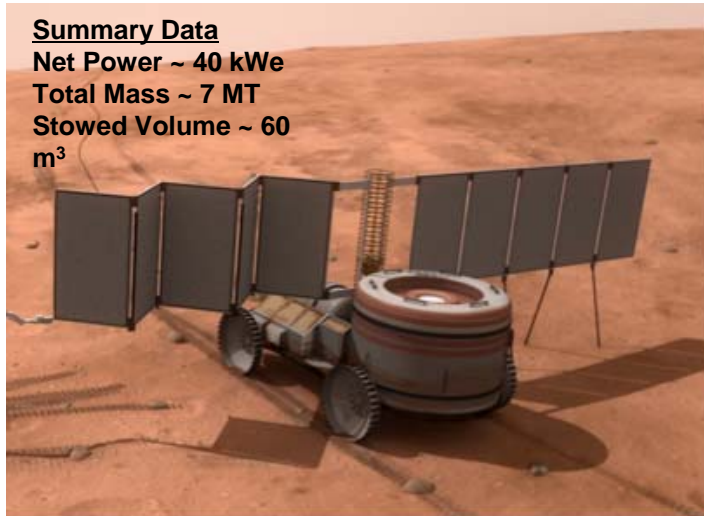
Fission Power System Reference Concept

- Modular 40 kWe system with 8-year design life suitable for (global) lunar and Mars surface applications
- Emplaced configuration with regolith shielding augmentation permits near-outpost siting (<5 rem/yr at 100 m separation)
- Low temperature, low development risk, liquid-metal (NaK) cooled reactor with UO_2 fuel and stainless steel construction

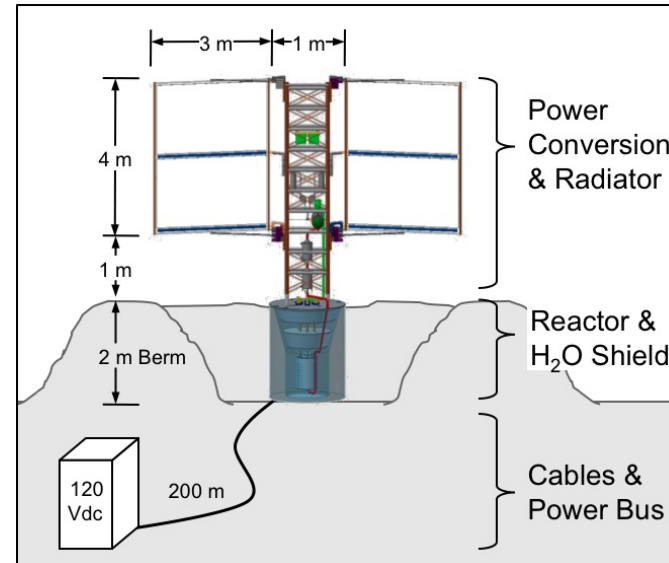




Mars Fission Surface Power System (FSPS)



Summary Data
 Net Power ~ 40 kWe
 Total Mass ~ 7 MT
 Stowed Volume ~ 60 m³



FSPS (kg)	10 kWe	40 kWe
Power Plant (Reactor, Power Conversion, Heat Rejection, Structure)	1615	3350
Radiation Shielding	1310	3000
Transmission Cabling	415	650
TOTAL	3340	7000

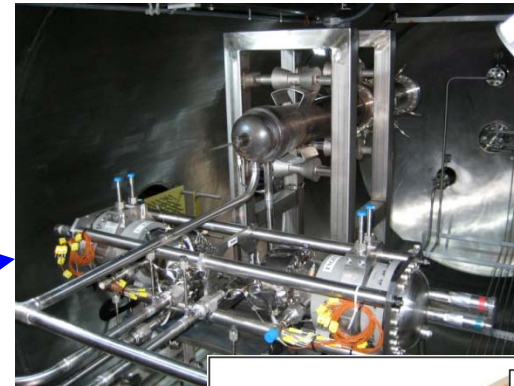
Reference: L.S. Mason and D.I. Poston, "A Summary of NASA Architecture Studies Utilizing Fission Surface Power Technology," NASA/TM-2011-216819, April 2011.



Fission Power System Technology Project

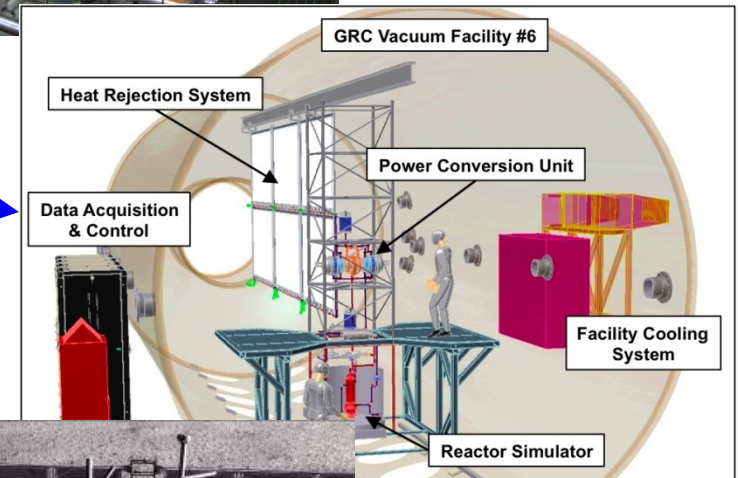
- Current FPS Project addresses mid-range Tech Readiness Levels:

- Sub-scale Pathfinder Component Tests
- Full-scale Technology Demonstration Unit (TDU) Integrated System Test
- Material & Component Irradiation Testing
- Concept Definition to support NASA Mission Studies



2 kWe NaK-Stirling Demo

TDU System Test



LSS Scenario 5:
Lander-Integrated
FSP System

- Objective is Non-Nuclear TRL6 by 2014

Completed FPS Pathfinders



NaK Reactor Simulator



NaK Stirling Demo



Full-scale Radiator



Electromagnetic Pump



Direct Gas-Cooled Brayton



Full-scale NaK Pump Test



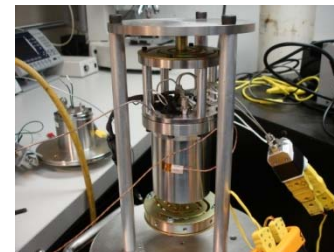
Pin Heater Demo



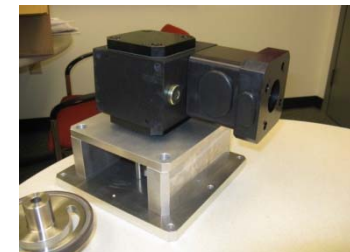
Titanium-Water Heat Pipes



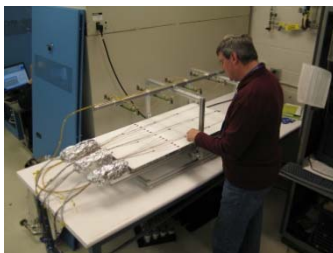
Stirling PMAD Demo



Alternator Radiation Test



Reactor Control Drive



Radiator Demonstration Unit



High Power Dual Brayton



Feasibility Test Loop



Thermodynamically-Coupled Stirling

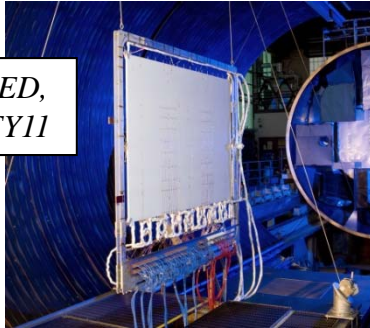
Fission Technology Demonstration Unit (TDU)

Government, Industry, & Academia Team Effort



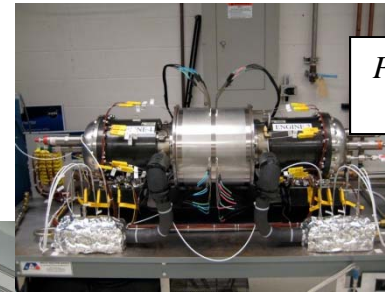
**Composite Heat Pipe
Radiator – GRC & Industry**

*PROTOTYPE TESTED,
TDU H/W RFP IN FY11*



**Stirling Power Conversion
Unit – GRC & Sunpower**

*PROTOTYPE TESTED,
TDU H/W IN FAB*



**Core Simulator – MSFC &
Los Alamos National Lab**



*PROTOTYPE TESTED,
TDU H/W COMPLETED*

*PROTOTYPE TESTED,
TDU H/W IN FAB*

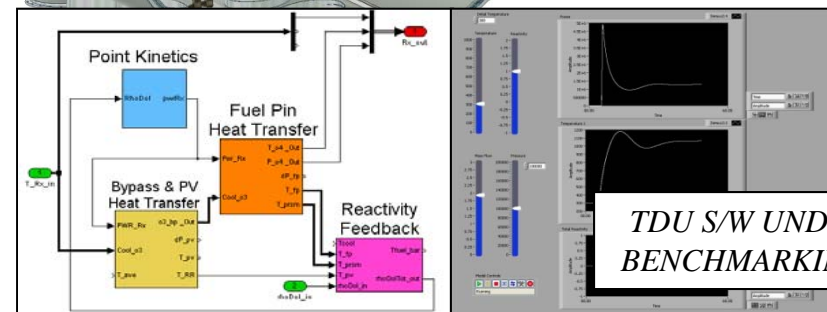
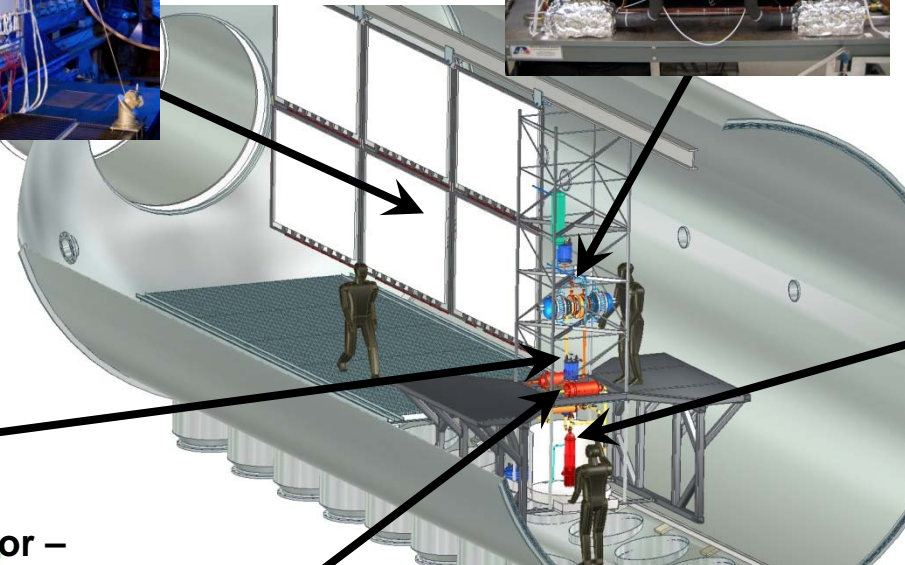


**NaK Volume Accumulator –
Oak Ridge National Lab**

*PROTOTYPE TESTED,
TDU H/W IN FAB*



NaK Pump – Idaho National Lab



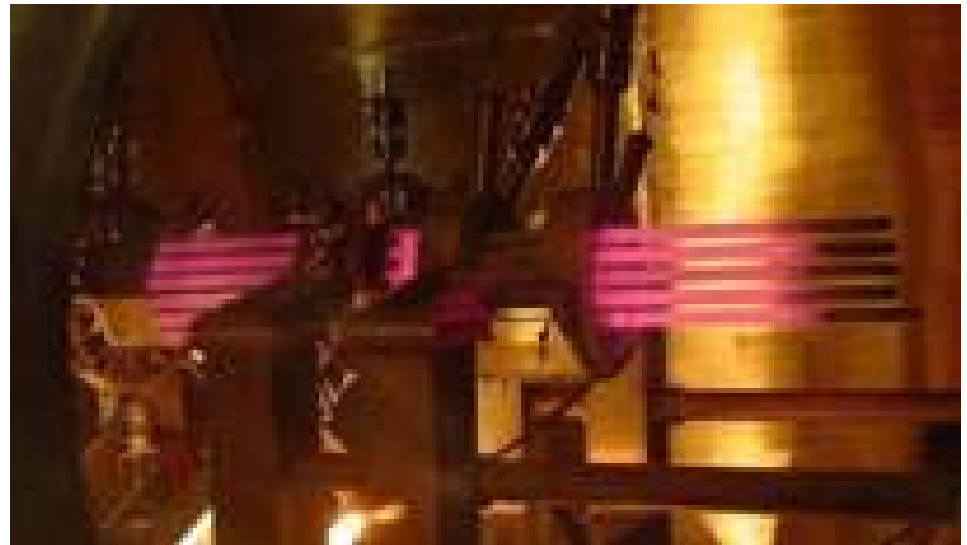
*TDU S/W UNDERGOING
BENCHMARKING TRIALS*

Reactor Simulation – Sandia National Lab

MSFC Early Flight Fission Test Facility (EFF-TF)



- Established in 1998, the MSFC Early Flight Fission Test Facility (EFF-TF) is designed to help enable affordable development of space fission systems.
- EFF-TF can perform highly realistic thermal hydraulic, heat transfer, structural, safety, and integrated system testing of space nuclear systems using non-nuclear (electrical) heat sources. Up to 8 MWe available power.
- Designed to test with any potential coolant. Heat pipe, gas cooled, and alkali metal cooled testing performed to date.
- Licensed for testing with natural and depleted uranium.





Safe Affordable Fission Engine (SAFE)

LANL Design, Fast-Spectrum U-235, Ex-Core Control, Be Reflected, Primary Heat Transport via Heat Pipes

Ultimate Goal: Perform realistic non-nuclear heated demonstrations of potential near-term space fission systems. Early focus is on core / heat exchanger.

Modular Unfueled Thermohydraulic Testing

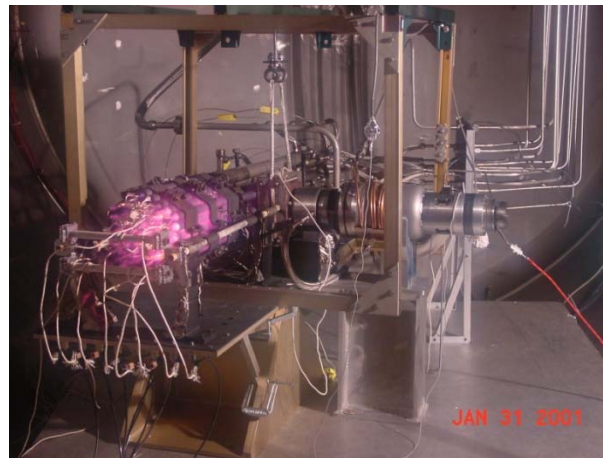


High-Temperature SAFE Module Testing Completed in FY00.

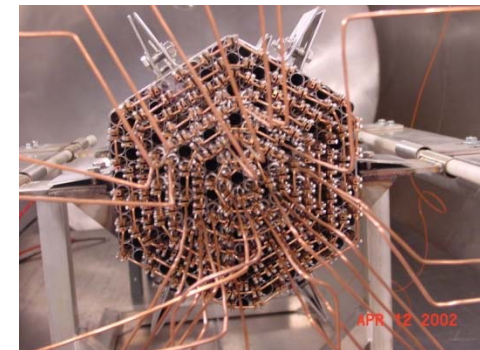
- > 1750 K Core Module Temperature.
- > 1450 K Heat pipe Temperature.
- Direct thermal propulsion mode demonstrated.
- Fast start of heat pipe (room temp to >1400 K in < 1 hr).
- Multiple heat pipe restarts.

SAFE-30 End-to-End

- Average core temperature above 600 deg C in over 20 core tests including both vacuum and CO₂ environments.
- 10 operating heat pipes with an evaporator exit temperature ~ 650 deg C, > 17 kW measured transferred to the calorimeters.
- Core and Stirling engine integrated with ion engine and tested at JPL. Testing completed Sept 2002. Demonstrated integrated system with heat generated in fuel pins converted to high specific impulse thrust.



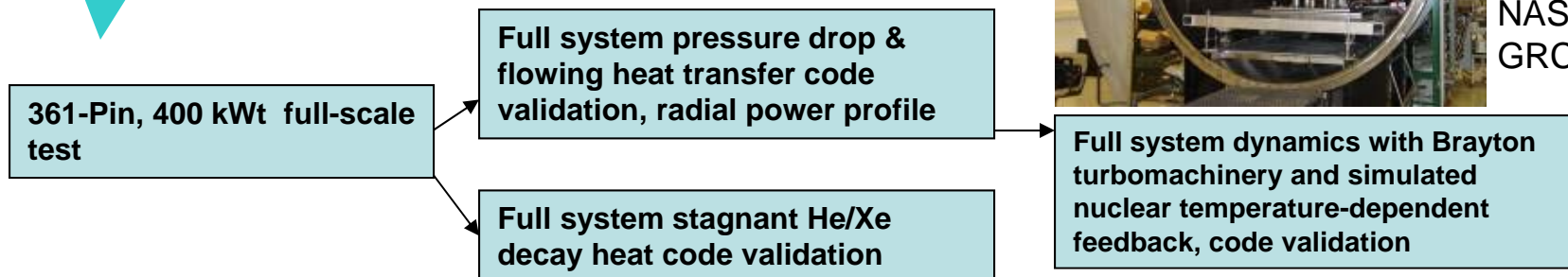
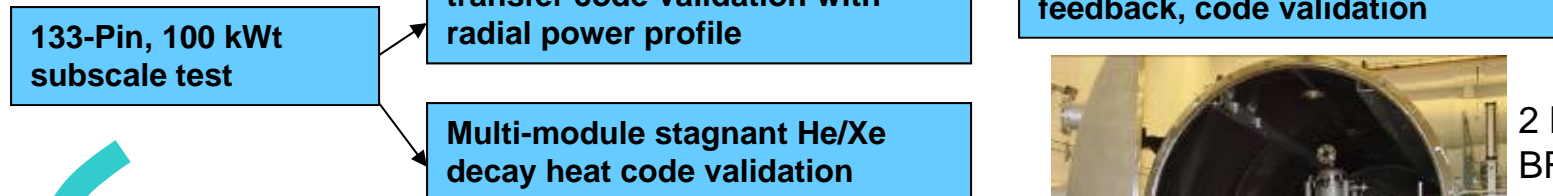
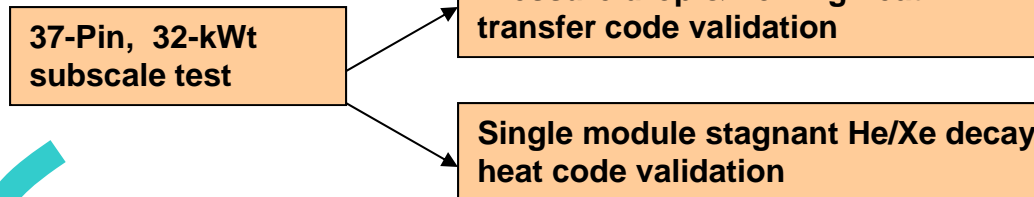
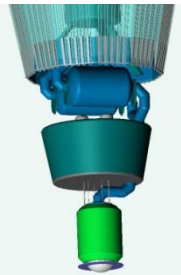
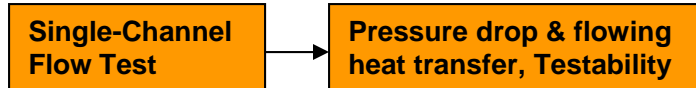
SAFE-100



- Computationally and experimentally investigate prototypic module, core, and heat exchanger design for 100 kWt system
 - Module fabrication
 - Core support / expansion
 - Thermal performance
 - Thermal cycling effects
- Develop and utilize advanced instrumentation and power delivery system.
 - 32 radial control zones
 - Heaters match axial power profile
 - Coarse matching of fuel pin thermal conductivity
- Develop / utilize high purity liquid metal handling capability at NASA MSFC.

Direct Drive Gas Cooled Reactor (DDG)

Sandia Design, Fast-Spectrum U-235, Ex-Core Control, Be Reflected, Primary Heat Transport via Noble Gas

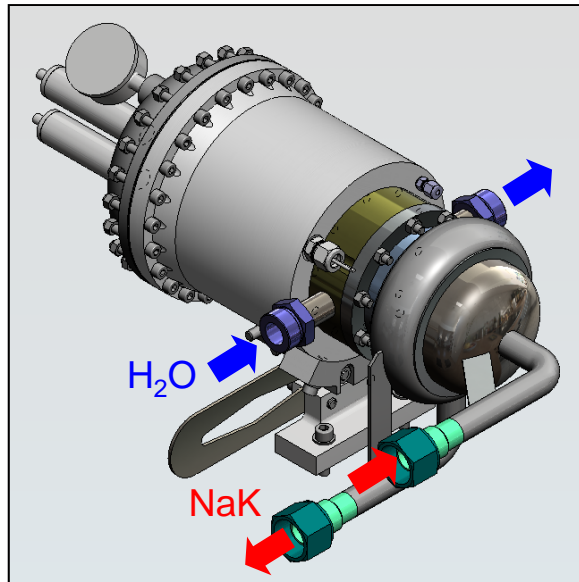


2 kWe BRU Test at NASA GRC

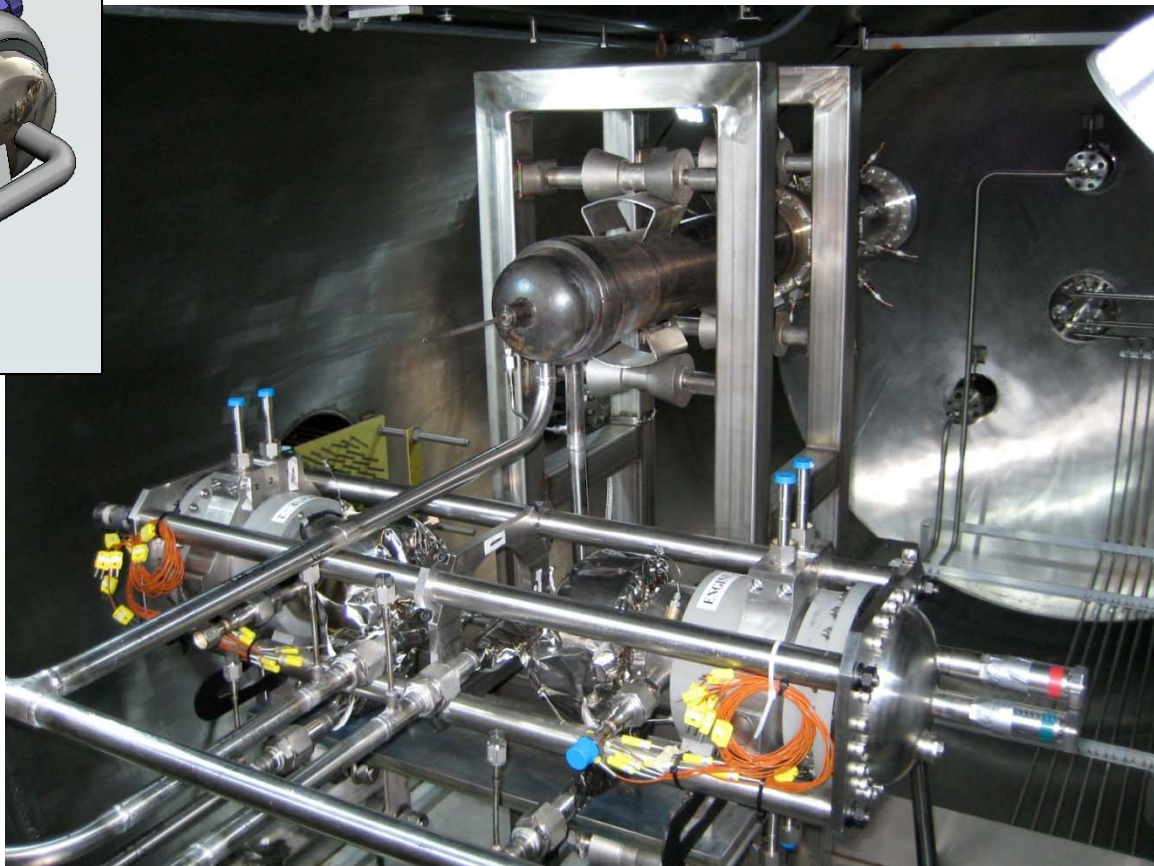
2 kWe NaK Stirling Demonstration Test



**Test Validated Reactor-Stirling
Heat Transfer Approach for FSP
(Stirling provided by NASA-GRC)**



- 2.4 kWe at $T_{hot}=550^{\circ}\text{C}$, $T_{cold}=50^{\circ}\text{C}$
- 32% Thermal Efficiency
- $<5^{\circ}\text{C}$ Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations



Coupled NaK Loop / Stirling Test



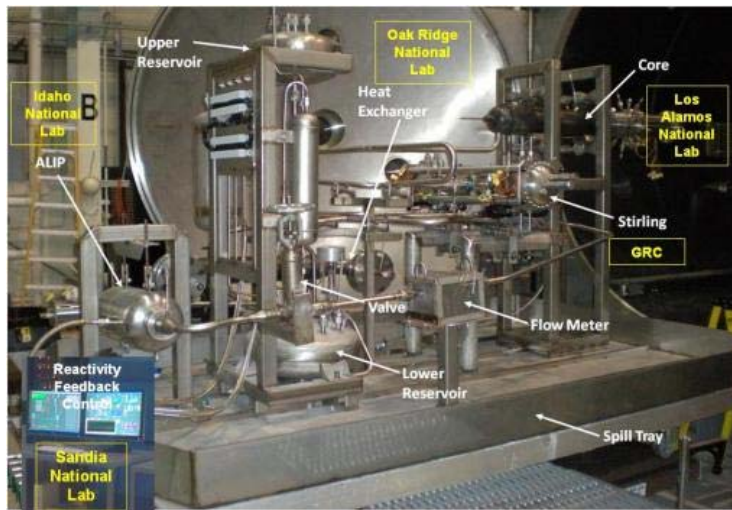
Cable tray providing protection from heat/NaK



Core Simulator Design by Los Alamos National Laboratory



Power Cable path to core



Integrated Stirling Test Assembly



ALIP Provided By Idaho National Laboratory

EFF-TF ALIP Test Circuit



Performance
Mapping of Annular
Linear Induction
Pump (ALIP)
provided by Idaho
National Laboratory



Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory



ALIP Test Circuit (ATC)



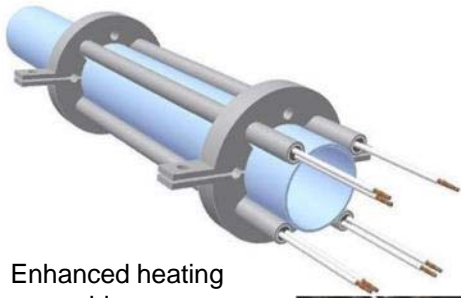
ALIP



ATC ready for chamber prior to NaK fill

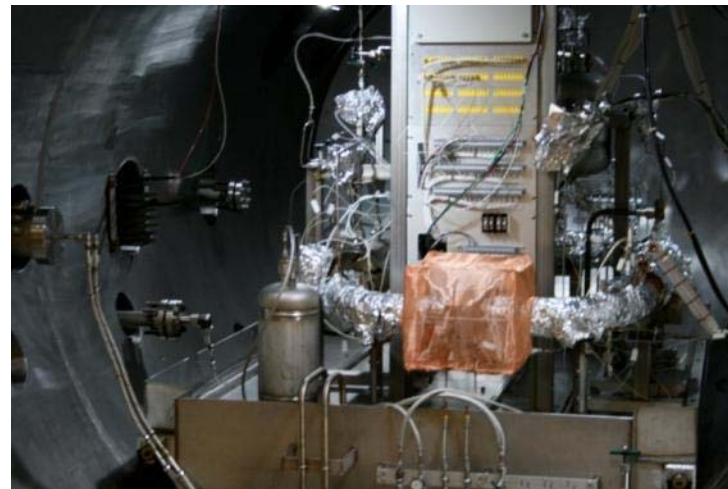


NaK fill



Enhanced heating assembly

Enhanced heating assembly ready for application of insulation



ATC Testing



EFF-TF Feasibility Test Loop



Feasibility Test Loop:
Investigate potential issues
and optimizations related to
pumped alkali metal systems

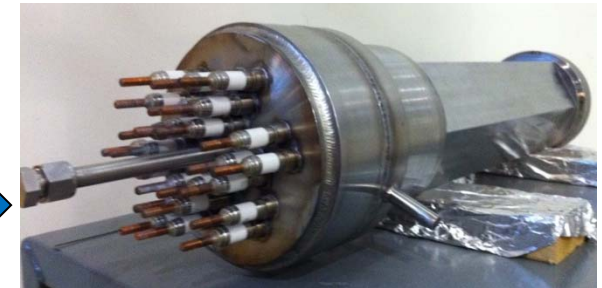
Fission Power System – Primary Test Circuit (FPS-PTC) 7 – Pin Reactor (Rx) Core Simulator Testing



MSFC
Designed
Advanced
Simulators



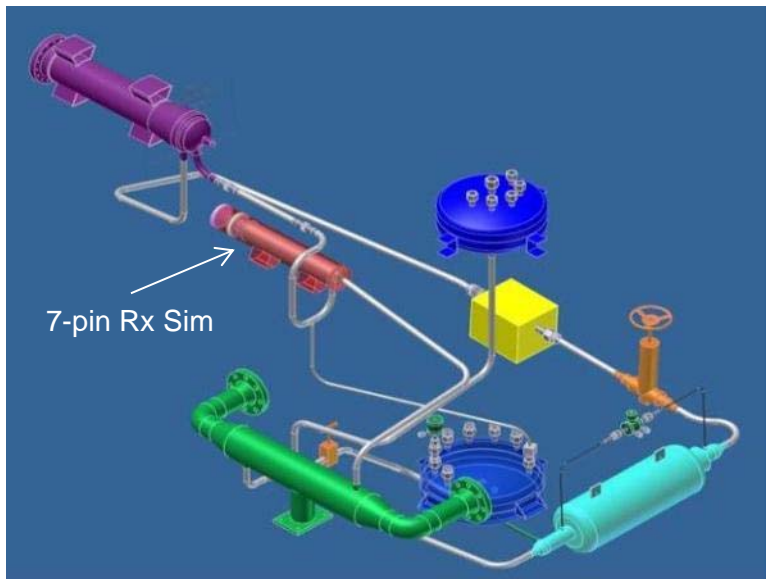
7-Pin Rx
Core Sim



37 – Pin TDU Rx Core Sim



7 – Pin Rx Core Sim Rendering



7-pin Rx Sim

Revised FPS-PTC layout for 7 – Pin Rx Core Sim



7-pin Rx Sim

7 Pin Rx Core Sim installed in FPS-PTC

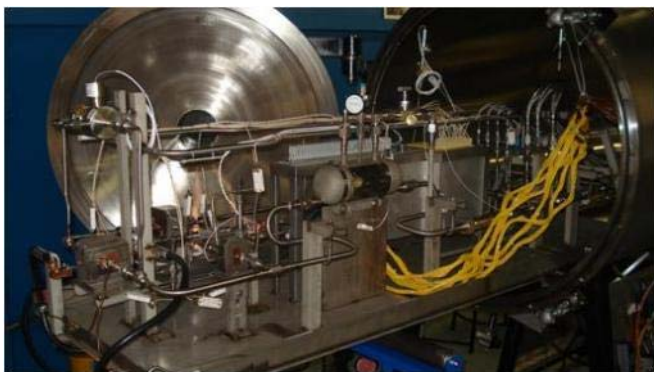
FPS Accomplishments



FPS-PTC
Stirling &
7 Pin Rx Core
Sim
Testing

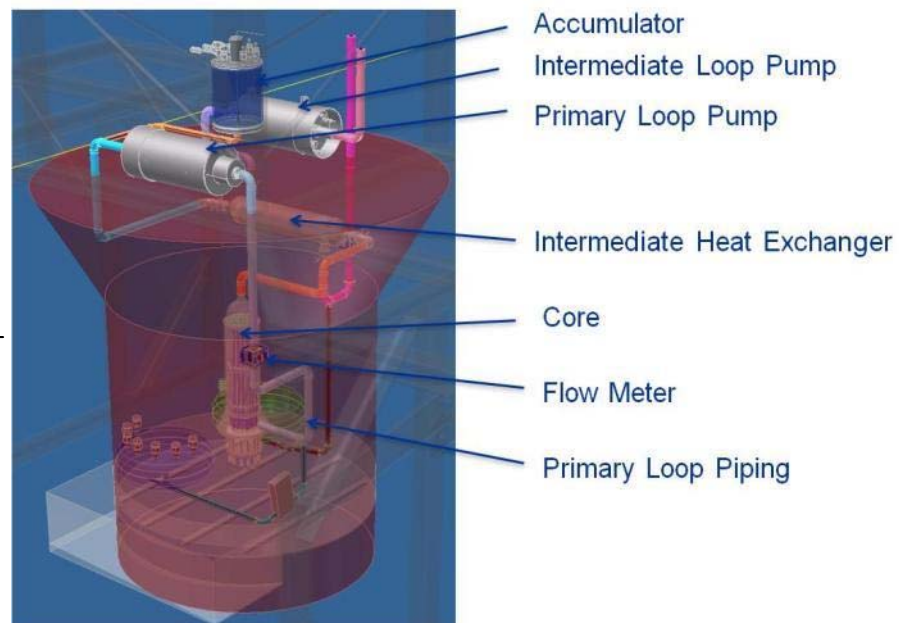


ATC
Testing



FTL
Testing

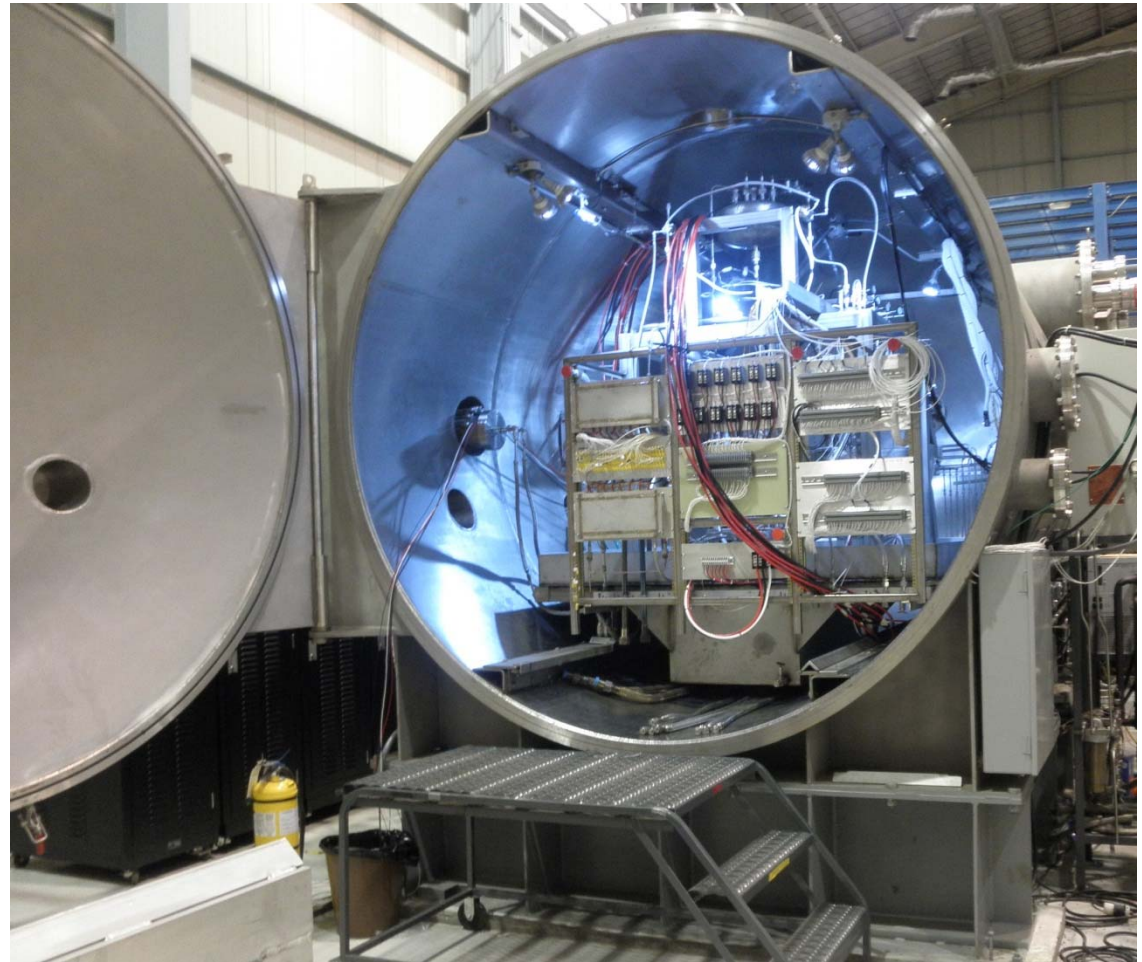
Recent Activities Focused Towards TDU Reactor Simulator



MSFC Designed Reactor Simulator in TDU
(top view close up)

MILESTONES
Fabricate & Test : 2010-2012
Ship to GRC 2012

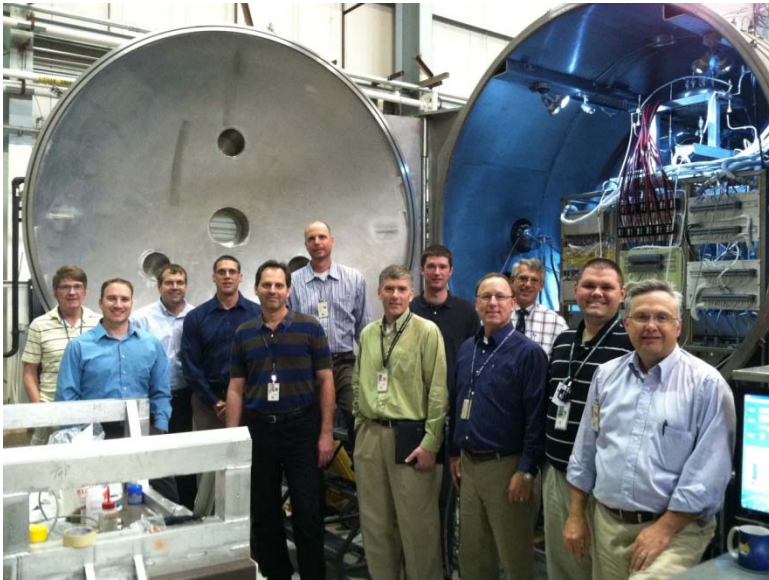
Fission Power Systems TDU Reactor (Rx) Simulator



Rx Sim in vacuum chamber for final checkouts

Currently being tested in the MSFC EFF-TF

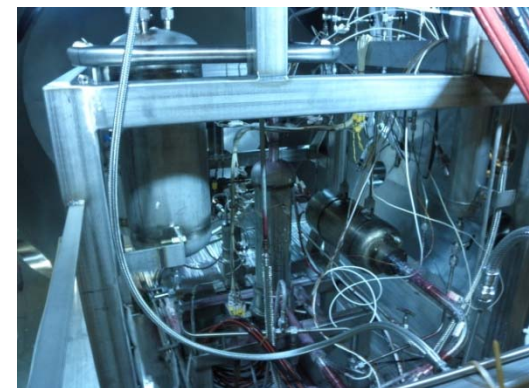
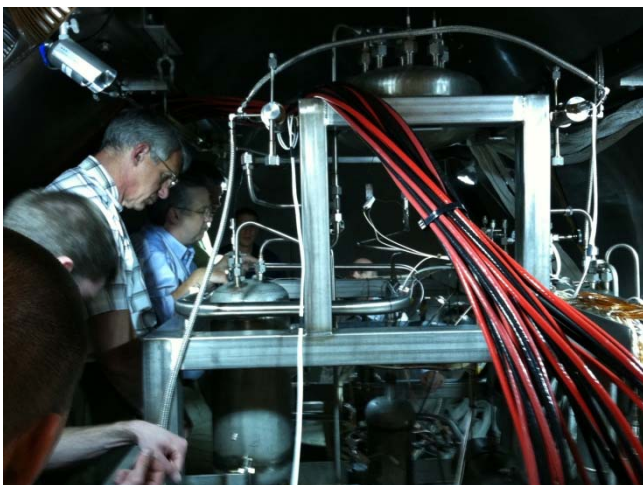
Fission Power Systems TDU Reactor (Rx) Simulator



Above: FPS Project Rx Sim Test Review Board and Project Team
Below: Don Palac (GRC) , FPS Project Manager is briefed by Boise Pearson, MSFC EFF-TF Team Lead



Above/Right: Rx Sim
NaK Fill



Above: Rx Sim in vacuum chamber during final checkouts

Summary



- Fission power and propulsion systems can enable exciting space exploration missions. These include bases on the moon and Mars; and the exploration, development, and utilization of the solar system.
- In the near-term, fission surface power systems could provide abundant, constant, cost-effective power anywhere on the surface of the Moon or Mars, independent of available sunlight. Affordable access to Mars, the asteroid belt, or other destinations could be provided by nuclear thermal rockets.
- In the further term, high performance fission power supplies could enable both extremely high power levels on planetary surfaces and fission electric propulsion vehicles for rapid, efficient cargo and crew transfer. Advanced fission propulsion systems could eventually allow routine access to the entire solar system. Fission systems could also enable the utilization of resources within the solar system.